Gravitational Wave Background and Non-Gaussianity as a Probe of the Curvaton Scenario

Kazunori Nakayama[(a)] and Jun'ichi Yokoyama[(b,c)]

[a]*Institute for Cosmic Ray Research (ICRR), University of Tokyo, Kashiwa, Chiba 277-8582, Japan*
[b]*Research Center for the Early Universe (RESCEU), Graduate School of Science, The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan*
[c]*Institute for the Physics and Mathematics of the Universe (IPMU), University of Tokyo, Kashiwa 277-8568, Japan*

Abstract

We study observational implications of the stochastic gravitational wave background and a non-Gaussian feature of scalar perturbations on the curvaton mechanism of the generation of density/curvature fluctuations, and show that they can determine the properties of the curvaton in a complementary manner to each other. Therefore even if Planck could not detect any non-Gaussianity, future space-based laser interferometers such as DECIGO or BBO could practically exhaust its parameter space.

1 Introduction

The idea of inflation [1] has become a standard paradigm since it was proposed in the early 1980's. Inflation is an accelerated expansion epoch in the very early Universe, which solves the flatness, the horizon and also the monopole problems naturally. Furthermore quantum fluctuation of the inflaton ϕ, which is a scalar field responsible for the accelerated expansion, can provide the seed of cosmic density/curvature fluctuations [2] observed through the cosmic microwave background (CMB) anisotropy [3], galaxy clustering, etc.

Another prediction of inflation, which is in fact more generic, is the generation of the stochastic gravitational wave background or the tensor perturbation, whose spectrum is nearly scale-invariant [4–34] (see Ref. [35] for a review). The amplitude of the gravitational wave is simply proportional to the Hubble parameter, H_{inf}, during inflation and many inflation models predict detectable amplitude of gravitational waves. In particular, future space-based gravitational wave detectors such as DECIGO [36] and/or BBO have a chance to detect inflationary gravitational wave background. Recently, it was pointed out that thermal history of the early universe is imprinted in the spectral shape of the gravitational wave background [14, 21, 28, 29, 31, 32]. In particular, the reheating temperature of the Universe after inflation can be determined or constrained from future gravitational wave experiments [29, 31, 32]. Thus any detection of primordial gravitational wave background gives useful information on the early Universe.

Traditionally, the spectrum of the comoving curvature perturbation is parametrized as

$$\Delta^2_{\mathcal{R}_c}(k) = \Delta^2_{\mathcal{R}_c}(k_*) \left(\frac{k}{k_*}\right)^{n_s-1}. \tag{1}$$

Here k_* is the pivot scale which we take $k_* = 0.002$ Mpc^{-1} and n_s is the scalar spectral index. Inflation predicts nearly scale-invariant spectrum with $n_s \cong 1$, with its precise value determined by the shape of the potential [2], and it agrees well with observations so far [3]. If ϕ has a single component with a canonical kinetic term, the resultant curvature fluctuation is Gaussian distributed, which is again in agreement with the observation today [3].

However, the origin of the density perturbation is not limited to the quantum fluctuation of the inflaton. Another scalar field, called curvaton, may be responsible for the generation of the observed density perturbation [37, 38]. It is undoubtedly an important task to distinguish them in order to understand the physics of the early Universe. One such signature may come from the non-Gaussianity in the CMB anisotropy [39], since the curvaton scenario can produce large enough non-Gaussian feature to be detected [40, 41], while standard inflation models predict negligible non-Gaussianity [42–45]. However, the situation where the curvaton generates large non-Gaussianity is somewhat limited and it is possible that the curvaton accounts for the observed density perturbation without generating large non-Gaussianity.

In this paper, we point out that the observation of stochastic gravitational wave background plays a very important role to probe the physics of the curvaton scenario. In the case that the curvaton generates negligible non-Gaussianity, there must be an entropy

production process by the curvaton decay itself, and such a non-standard thermal history is imprinted in the spectrum of the inflationary gravitational wave background. Future space-based gravitational wave detectors, such as DECIGO and/or BBO may be able to do this job. This opens up a possibility to find an evidence of the curvaton scenario. Thus measurement of the non-linearity parameter $f_{\rm NL}$ which is a simplified measure of non-Gaussianity and that of tensor perturbations by DECIGO/BBO play complementary roles to each other.

The rest of the paper is organized as follows. In Sec. 2, the gravitational wave background spectrum and non-Gaussianity in the curvaton scenario are summarized. In Sec. 3 the detection possibility is discussed. Sec. 4 is devoted to the conclusion.

2   Features of the Curvaton Scenario

In this section, we summarize the cosmological consequences of the curvaton scenario, namely, the spectra of gravitational wave background and the density/curvature perturbation, and non-Gaussianity. All these ingredients are essential for probing the curvaton scenario and constraining the parameter space, as will be discussed in Sec. 3.

2.1   Gravitational wave background spectrum in the curvaton scenario

In the inflationary era, quantum fluctuations of the RMS amplitude of $H_{\rm inf}/(2\pi)$ are induced on all massless fields in each Hubble time. Here "massless" means that the mass is much smaller than $H_{\rm inf}$. The tensor perturbation of the metric consists of two free massless scalar components, which can be quantized in de-Sitter space-time. After a mode left the horizon during inflation, it actually becomes a classical fluctuation which can be viewed as a stochastic gravitational wave. Thus inflation necessarily generates a gravitational wave background from a cosmological scale to a sub-kilometer scale The former is a target of detection by the B-mode polarization of CMB anisotropy and direct detection by space-based laser interferometer experiments.

Tensor perturbation of the metric is defined by the following line element,

$$ds^2 = a(\tau)^2 \left[-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j \right], \tag{2}$$

where $a(\tau)$ is the scale factor and h_{ij} denotes the metric perturbation satisfying the transverse-traceless conditions $\partial^i h_{ij} = 0$ and $h^i_i = 0$. Thus h_{ij} has two physical degrees of freedom, which are denoted as h^λ with $\lambda = +, \times$. In the inflationary era, the tensor perturbation has a quantum fluctuation whose spectrum is given by

$$\Delta_h^{(\rm p)2}(k) = 64\pi G \left(\frac{H_{\rm inf}}{2\pi} \right)^2 \left(\frac{k}{k_*} \right)^{n_t}, \tag{3}$$

where the tensor spectral index is given by $n_t = -2\epsilon$. Here ϵ is one of the slow-roll parameters during inflation defined by

$$\epsilon = \frac{M_{\mathrm{Pl}}^2}{2}\left(\frac{V'}{V}\right)^2, \qquad \eta = M_{\mathrm{Pl}}^2\frac{V''}{V}, \tag{4}$$

where V is the inflaton potential and the prime denotes derivative with respective to the inflaton field ϕ, and $M_{\mathrm{Pl}} = (8\pi G)^{-1/2}$ is the reduced Planck scale.

After the production of the gravitational waves during inflation, the amplitude of each Fourier mode remains constant when the corresponding mode lies outside the Hubble radius. However, once it enters the horizon, its amplitude decreases as $\propto a^{-1}$. Thus the present energy density of the gravitational wave background per logarithmic frequency interval is written as

$$\frac{d\rho_{\mathrm{gw}}}{d\ln k} = \frac{k^2}{32\pi G a_0^2}\Delta_h^{(\mathrm{p})2}(k)\left(\frac{a_{\mathrm{in}}(k)}{a_0}\right)^2, \tag{5}$$

where a_0 is the present scale factor, and $a_{\mathrm{in}}(k)$ denotes the scale factor at which the corresponding mode with wave number k enters the horizon. It behaves as $\propto k^{-2}(k^0)$ for the mode which enters the horizon at matter (radiation) dominated era. Therefore thermal history of the Universe is imprinted in the spectrum of the gravitational wave background, and this is the reason why the observations of the gravitational wave are expected to have great impacts on cosmology [14, 21, 28, 31, 32].

In terms of the density parameter, it can be rewritten as

$$\Omega_{\mathrm{gw}}(k) = \frac{k^2}{12a_0^2 H_0^2}\Delta_h^2(k), \tag{6}$$

where H_0 is the present Hubble parameter, and

$$\Delta_h^2(k) = \Delta_h^{(\mathrm{p})2}(k)\Omega_{\mathrm{m}}^2\left(\frac{3j_1(z_k)}{z_k}\right)^2\left(\frac{g_*(T_{\mathrm{in}})}{g_{*0}}\right)\left(\frac{g_{*s0}}{g_{*s}(T_{\mathrm{in}})}\right)^{4/3}T_1^2(x_{\mathrm{eq}})T_2^2(x_{\mathrm{R}}), \tag{7}$$

where $g_*(T_{\mathrm{in}})$ denotes the effective relativistic degrees of freedom at the temperature T_{in} when k-mode enters the horizon, and $j_1(z)$ is the spherical Bessel function of the first rank with $z_k \equiv 2k/(a_0 H_0)$.[1] The transfer functions $T_1(x)$ and $T_2(x)$ are given by [8, 32]

$$T_1^2(x) = 1 + 1.57x + 3.42x^2, \tag{8}$$
$$T_2^2(x) = [1 - 0.32x + 0.99x^2]^{-1}. \tag{9}$$

The former connects the gravitational wave spectrum of the mode entering the horizon before ($x_{\mathrm{eq}} \equiv k/k_{\mathrm{eq}} > 1$) and after ($x_{\mathrm{eq}} < 1$) the matter-radiation equality, where $k_{\mathrm{eq}} \equiv a(t_{\mathrm{eq}})H(t_{\mathrm{eq}}) = 7.3 \times 10^{-2}\Omega_{\mathrm{m}}h^2$ Mpc^{-1}.[2] The latter transfer function connects the mode

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[1] There was an error in Eq. (14) of Ref. [32]. Eq. (7) is the correct one.

[2] The effect of neutrino free streaming is known to lead a suppression on the gravitational wave background spectrum around the frequency $\sim 10^{-9}$ Hz [15, 26]. But our concern is around 1 Hz, and hence we simply neglect this effect.

entering the horizon before ($x_{\rm R} \equiv k/k_{\rm R} > 1$) and after ($x_{\rm R} < 1$) the reheating subsequent to inflation. Here $k_{\rm R}$ is the comoving wavenumber corresponding to the horizon scale at the reheating epoch when the Universe became radiation dominant. Without any significant entropy production after the reheating, it is given by

$$\frac{k_{\rm R}}{a_0} = 1.7 \times 10^{13} \text{ Mpc}^{-1} \left(\frac{g_{*s}(T_{\rm R})}{106.75} \right)^{1/6} \left(\frac{T_{\rm R}}{10^6 \text{ GeV}} \right),$$
$$T_{\rm R} = \left(\frac{10}{\pi^2 g_*(T_{\rm R})} \right)^{1/4} \sqrt{\Gamma_\phi M_{\rm Pl}},$$

(10)

with $T_{\rm R}$ and Γ_ϕ being the reheating temperature after inflation and the decay rate of the inflaton, respectively. This corresponds to the frequency $f = 0.026$Hz for $T_{\rm R} = 10^6$GeV, which is close to the most sensitive frequency range of the planned future space-based laser interferometer experiments, DECIGO or BBO. Thus by observing the spectral shape of the gravitational wave background, the reheating temperature of the Universe can be determined or constrained.

As mentioned above, the above correspondence assumes the standard thermal history with no significant entropy production after reheating. In the curvaton scenario, however, its coherent oscillation may once dominate the Universe, which introduces an additional matter-dominated era, and then decays releasing huge amount of entropy. In this case the gravitational wave spectrum receives an additional suppression [14, 31, 32] which can be quantified by the dilution factor, F, defined by

$$F = \frac{s(T_\sigma) a^3(T_\sigma)}{s(T_{\rm R}) a^3(T_{\rm R})} = \begin{cases} \dfrac{\sigma_i^2}{6 M_{\rm Pl}^2} \dfrac{T_{\rm R}}{T_\sigma} & \text{for} \quad m_\sigma > \Gamma_\phi \\ \dfrac{\sigma_i^2}{6 M_{\rm Pl}^2} \dfrac{T_{\rm osc}}{T_\sigma} & \text{for} \quad m_\sigma < \Gamma_\phi \end{cases}, \tag{11}$$

where Γ_ϕ is the decay rate of the inflaton, T_σ is the radiation temperature just after the curvaton decay, and $T_{\rm osc}$ is the temperature at which the curvaton begins to oscillate. This expression is valid for $F \gg 1$. The resultant gravitational wave spectrum is given by

$$\Delta_h^2(k) = \Delta_h^{({\rm p})2}(k) \Omega_{\rm m}^2 \left(\frac{3 j_1(z_k)}{z_k} \right)^2 \left(\frac{g_*(T_{\rm in})}{g_{*0}} \right) \left(\frac{g_{*s0}}{g_{*s}(T_{\rm in})} \right)^{4/3}$$
$$\times T_1^2(x_{\rm eq}) T_2^2(x_\sigma) T_1^2(x_{\sigma {\rm R}}) T_2^2(x_{\rm R}(F)),$$

(12)

where $x_\sigma = k/k_\sigma$ with k_σ given in an analogous way with (10) after replacing $T_{\rm R}$ with T_σ, and $x_{\sigma {\rm R}} = k/k_{\sigma {\rm R}}$ with $k_{\sigma {\rm R}} = k_\sigma F^{2/3}$ and $x_{\rm R}(F) = k/k_{\rm R}(F)$ with $k_{\rm R}(F) = k_{\rm R} F^{-1/3}$.

In Fig. 1 we show spectra of the gravitational wave background as a function of its present frequency. In the top panel, the spectra for $H_{\rm inf} = 10^{14}$ GeV and 10^{13} GeV with the reheating temperature $T_{\rm R} = 10^6$ GeV are shown. Also plotted are sensitivities of DECIGO with a correlation analysis (blue dashed line), ultimate-DECIGO (red dotted line), and correlation of analysis of ultimate-DECIGO (purple dot-dashed line) [20]. In the bottom panel, the gravitational wave background spectra in the presence of entropy production is shown, for $F = 10$ and $T_\sigma = 10$ GeV and $T_{\rm R} = 10^7$ GeV.
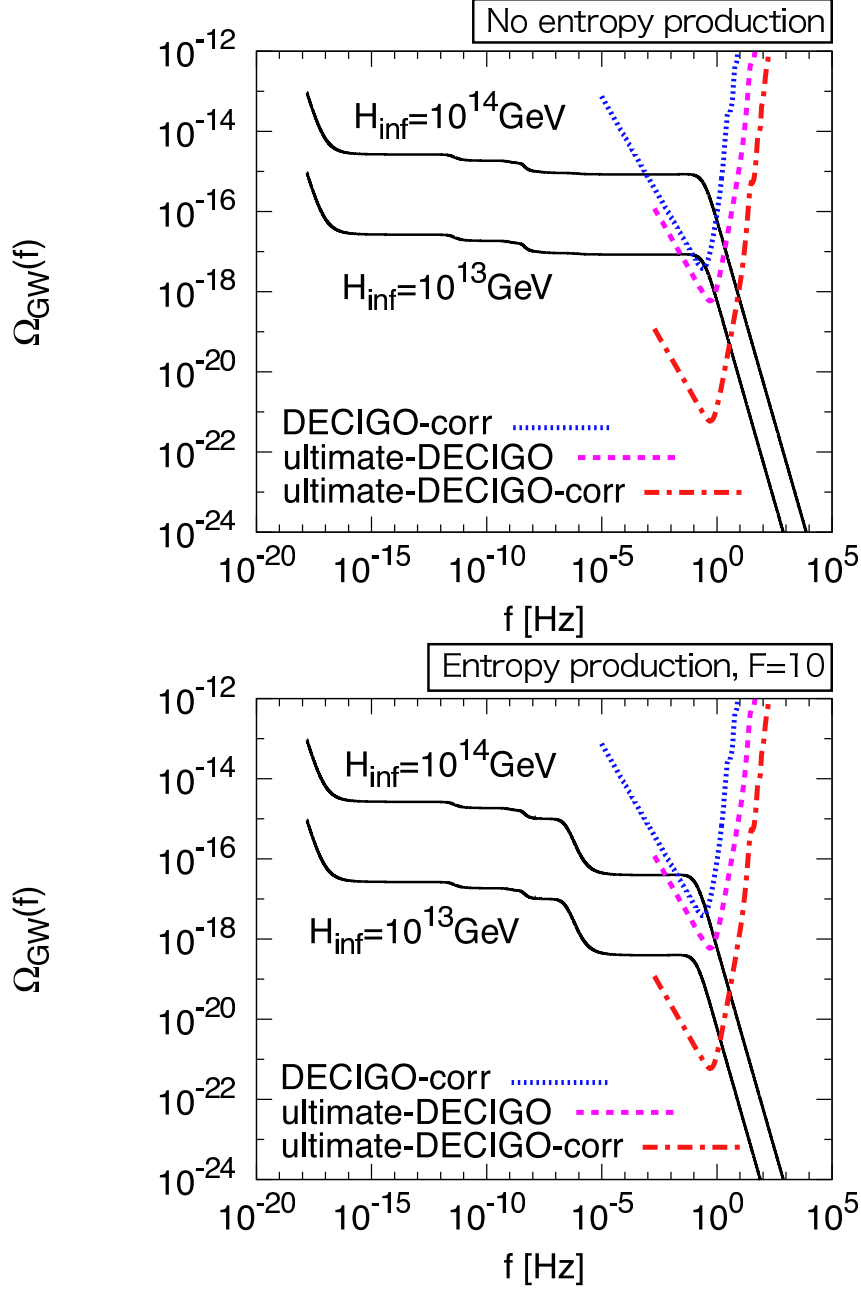
Figure 1: (Top) Spectra of the gravitational wave background for inflationary scale $H_{\text{inf}} = 10^{14}$ GeV and 10^{13} GeV. Here we have taken $T_{\text{R}} = 10^7$ GeV. Also shown are sensitivities of planned space-based gravitational wave detectors, DECIGO with a correlation analysis (blue dashed line), ultimate-DECIGO (purple dotted line), and correlation of analysis of ultimate-DECIGO (red dot-dashed line). (Bottom) Same as the top panel for the dilution factor $F = 10$ for $T_\sigma = 10$ GeV and $T_{\text{R}} = 10^7$ GeV.

2.2 Scalar perturbation in the curvaton scenario

The curvaton is a scalar field other than the inflaton, which remains light during inflation and has a quantum fluctuation $\delta\sigma \sim H_{\text{inf}}/(2\pi)$. Then, according to the δN-formalism [46], the comoving curvature perturbation $\mathcal{R}_c$ is given by

$$\mathcal{R}_c = N_\sigma \delta\sigma + \frac{1}{2} N_{\sigma\sigma}(\delta\sigma)^2, \tag{13}$$

up to the second order in $\delta\sigma$, where N is the local number of e-folds, given by the integral of the local expansion from an initial spatially flat hypersurface to a final uniform density hypersurface, and N_σ is its derivative with respective to σ. Note that we assume the curvaton behaves as free scalar field and hence $\delta\sigma$ can be regarded as a random Gaussian variable. Then we obtain [47]

$$\mathcal{R}_c = \frac{2R}{3}\left(\frac{\delta\sigma}{\sigma_i}\right) + \left(\frac{R}{3} - \frac{4R^2}{9} - \frac{2R^3}{9}\right)\left(\frac{\delta\sigma}{\sigma_i}\right)^2, \tag{14}$$

where σ_i is the initial amplitude of the curvaton during inflation, and

$$R = \left.\frac{3\rho_\sigma}{4\rho_r + 3\rho_\sigma}\right|_{\sigma \text{ decay}} \tag{15}$$

roughly denotes the fraction of the curvaton energy density to the total energy density at the epoch of curvaton decay. Here ρ_σ and ρ_r are the energy densities of the curvaton and that of radiation, respectively. In order to reproduce the observed density perturbation of the Universe, we must have

$$\sqrt{\Delta_{\mathcal{R}_c}^2(k_*)} = \frac{R}{3}\left(\frac{H_{\text{inf}}}{\pi\sigma_i}\right) = 5 \times 10^{-5}. \tag{16}$$

Notice that the inflaton also generates curvature perturbation whose magnitude is $\Delta_{\mathcal{R}_c\phi}^2 = H_{\text{inf}}^2/(8\pi^2\epsilon M_{\text{Pl}}^2)$. It is much smaller than curvaton's contribution (16) by assumption. This leads to a constraint

$$\epsilon > \frac{9}{8R^2}\left(\frac{\sigma_i}{M_{\text{Pl}}}\right)^2 = 9 \times 10^{-3}\left(\frac{H_{\text{inf}}}{10^{14} \text{ GeV}}\right)^2, \tag{17}$$

where we have used the WMAP normalization (16). We can calculate the tensor-to-scalar ratio r in the curvaton scenario, as

$$r \equiv \frac{\Delta_h^2(k_*)}{\Delta_{\mathcal{R}_c}^2(k_*)} = \frac{18}{R^2}\left(\frac{\sigma_i}{M_{\text{Pl}}}\right)^2 = 0.14\left(\frac{H_{\text{inf}}}{10^{14}\text{GeV}}\right)^2. \tag{18}$$

It can be checked that this is smaller than 16ϵ using Eq. (17), which is the prediction of the standard inflation scenario, once we assume that the curvature perturbation from the inflaton should be smaller than that from the curvaton.

The scalar spectral index is given by [38]

$$n_s = 1 - 2\epsilon + \frac{2m_\sigma^2}{3H_{\text{inf}}^2}, \tag{19}$$

where m_σ is the curvaton mass. We can determine it through the relation

$$m_\sigma^2 = \frac{3}{2}(n_s - n_t - 1)H_{\text{inf}}^2 = 11(n_s - n_t - 1)r \times (10^{14}\text{GeV})^2, \tag{20}$$

in principle. But it is generically much smaller than H_{inf}^2, so that it would be more practical to use the above equality as a consistency relation,

$$n_s - n_t \cong 1, \tag{21}$$

for the curvaton scenario.

Thus in the curvaton scenario, both the scalar and tensor spectral tilt are predicted to be -2ϵ, and hence a measurement of the tensor spectral index by future space-based gravitational wave detectors [19] will give an evidence of the curvaton scenario.

2.3 Non-Gaussianity in the curvaton scenario

Statistics of the observed CMB anisotropy is currently consistent with Gaussian distribution. The deviation from Gaussianity is parameterized by the non-linearity parameter f_{NL}, whose definition is given by

$$\mathcal{R}_c = \mathcal{R}_c^{(g)} + \frac{3}{5}f_{\text{NL}}\mathcal{R}_c^{(g)2}, \tag{22}$$

where $\mathcal{R}_c^{(g)}$ denotes the Gaussian part of the curvature perturbation. WMAP5 result gives a constraint on it as $-9 < f_{\text{NL}} < 111$ at 95% C.L. [3]. From Eq. (14), we can estimate the non-linearity parameter as[3]

$$f_{\text{NL}} = \frac{5}{4R}\left(1 - \frac{4}{3}R - \frac{2}{3}R^2\right). \tag{23}$$

Thus f_{NL} can be significantly large for small R, and this may provide an observational hint of the curvaton scenario if large f_{NL} is detected, because standard inflation models predict a small non-linearity parameter, $f_{\text{NL}} \sim \mathcal{O}(\epsilon, \eta)$. Here we have assumed that the curvaton potential is quadratic, $V = (1/2)m_\sigma^2\sigma^2$. If it deviates from the quadratic one, the prediction of f_{NL} changes [41] and in this case the coefficient of the trispectrum, g_{NL}, may be useful to distinguish curvaton models. We do not go into the detail on this point.

Notice that in the case where a large non-Gaussianity ($f_{\text{NL}} \gtrsim 10$) is obtained, the curvaton decay does not increase entropy because it must be a subdominant component

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[3] Here we assume that there are no CDM/baryonic isocurvature perturbations, which might cause other types of non-Gaussianity [48–50].

at the instance of its decay (*i.e.*, $R \ll 1$), so that the gravitational wave background spectrum is not modified. In this sense, the detections of f_{NL} by the CMB observation and entropy production process by the gravitational wave background as a probe of the curvaton scenario are complementary to each other.

To summarize, we have five possible observable quantities: scalar spectral index n_s, tensor-to-scalar ratio r, tensor spectral index n_t, the dilution factor F and non-linearity parameter f_{NL}. Among them, r will be accurately determined by future B-mode polarization measurements. Direct detection of gravitational waves will observe n_t, and comparing it with n_s will confirm the curvaton scenario. Then, either large enough F or f_{NL} will be observed depending on whether the curvaton once dominated the Universe or not. In the former case, F can be determined by comparing r and directly observed magnitude of the gravitational waves. In the latter case, f_{NL} will be determined by CMB measurements such as Planck. Then these observables may be used to pin down a curvaton model.

In the next section we investigate the possibility to detect either signature of the curvaton scenario and how they can fix properties of the curvaton.

3   Probing the Curvaton Scenario

We have seen that a curvaton scenario may leave distinct signatures on either a shape of the gravitational wave background or primordial non-Gaussianity. Here we show parameter regions where a curvaton scenario has characteristic features on either of them.

Curvaton models are characterized by two parameters, the initial amplitude of the curvaton σ_i and its decay temperature T_σ. The relevant quantity is the abundance of the curvaton coherent oscillation at the time of its decay, which depends on these two parameters and the reheating temperature after inflation, T_{R}, but does not depend on the curvaton mass.[4]   Once these parameters are fixed, we can estimate the inflation scale H_{inf} in order to reproduce the observed magnitude of the density perturbation (see Eq. (16)). The inflation scale H_{inf} also gives overall normalization of the gravitational wave background spectrum, which can be directly measured independently using B-mode polarization of CMB. The spectral shape is determined by T_{R} and the curvaton abundance at its decay. Thus we can uniquely predict the gravitational wave signal at an arbitrary frequency for each parameter set $(T_{\mathrm{R}}, T_\sigma, \sigma_i)$. Similarly, the level of non-Gaussianity depends only on the curvaton abundance at its decay, as given in Eq. (23), and hence is also uniquely predicted.

Figures 2 depict the parameter region of the curvaton which can be probed by observation of DECIGO/BBO. The upper panel represents the region accesible with a single ultimate-DECIGO and B-mode experiments such as EPIC [51], CMBPol [52], and Lite-BIRD [53] which are expected to reach down to $r \simeq 10^{-3}$. The lower panel shows the ideal case of correlation analysis of ultimate-DECIGO together with low-noise delensed

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[4] If the curvaton begins to oscillate after the inflaton decays, the mass dependence appears. In this case, however, it is sufficient to replace T_{R} with T_{osc}, the temperature at which the curvaton begins to oscillate, as in Eq. (11).

CMB map which would hopefully reach $r \sim 2 \times 10^{-6}$ [54] (see also [55]).

Sensitivities of these direct detection experiments for the low frequency are limited by stochastic noise from white dwarf binaries [56], and hence we have cut the sensitivities below 0.1 Hz. We have set ϵ to satisfy the constraint (17), but the precise value of ϵ does not affect the results as long as it is sufficiently small. The region above the purple wedge corresponds to $r > 0.2$ which is excluded by WMAP.

Also plotted there are contours of the non-linearity parameter $f_{\rm NL}$ and the dilution factor F. The region with $f_{\rm NL} > 100$ is also disfavored by WMAP. On the other hand, Planck can measure it if it lies in the range $10 < f_{\rm NL}$. As argued before, it occupies a detached domain from the region with $F > 1$. Therefore below we study how the curvaton parameters are determined in each domain separately.

First let us consider the case $f_{\rm NL} \gg 1$ is confirmed by, say, Planck experiment. Then from (23) we find $R \cong 5/(4f_{\rm NL})$ and therefore (18) determines the initial amplitude of the curvaton in terms of the observable quantities alone as

$$
\frac{\sigma_i}{M_{\rm Pl}} = \frac{5}{12 f_{\rm NL}} \left(\frac{r}{2} \right)^{1/2} .
\tag{24}
$$

In this case the curvaton decays before dominating the cosmic energy density. Hence we find

$$
\left. \frac{\rho_\sigma}{\rho_r} \right|_{\sigma \ \rm decay} = \frac{1}{6} \left(\frac{\sigma_i}{M_{\rm Pl}} \right)^2 \frac{a(T_\sigma)}{a(T_{\rm R})} = \frac{1}{6} \left(\frac{\sigma_i}{M_{\rm Pl}} \right)^2 \frac{T_{\rm R}}{T_\sigma} \cong \frac{4}{3} R.
\tag{25}
$$

These two equalities lead to

$$
\frac{T_\sigma}{T_{\rm R}} = \frac{5r}{576 f_{\rm NL}}.
\tag{26}
$$

Thus both of the curvaton parameters are fixed by the observable quantities in this case. Finally we note that in this case there is a simple relation between $T_\sigma/T_{\rm R}$ and $\sigma_i/M_{\rm Pl}$ as

$$
\frac{T_\sigma}{T_{\rm R}} = \frac{f_{\rm NL}}{10} \left(\frac{\sigma_i}{M_{\rm Pl}} \right)^2 ,
\tag{27}
$$

which was used to draw the contours of $f_{\rm NL}$ in Figures 2.

Next we consider the case the curvaton dominates the energy density of the universe when it decays releasing significant amount of entropy with $R = 1$ and $F > 1$. Then from (18) we find

$$
\frac{\sigma_i}{M_{\rm Pl}} = \left(\frac{r}{18} \right)^{1/2}
\tag{28}
$$

and from (11) we obtain

$$
\frac{T_\sigma}{T_{\rm R}} = \frac{r}{108F},
\tag{29}
$$

for $T_{\rm osc} > T_{\rm R}$. We can determine F if we can measure tensor perturbations both by the B-mode polarization of CMB and DECIGO/BBO, provided there is no other source of entropy production mechanism after reheating besides the curvaton. Then all the relevant

parameters are again fixed by the observable quantities. The corresponding parameter space is shown by the orange regions in Figs. 2. In case there is other entropy production besides curvaton, the right-hand-side of (29) will give a lower bound on T_σ/T_R. Finally, if B-mode polarization measurements fail to find the tensor mode and if it is detected only by DECIGO/BBO, which is shown by the yellow regions in Figs. 2, the values of F and r cannot be determined independently. Only the combination $rF^{-4/3}$ is determined in this case.

4   Conclusion

In this paper we have investigated a possible observable signatures from curvaton scenarios, including non-Gaussianity, detection of tensor modes in CMB and direct detection of gravitational wave background. First the measurement of the tensor power spectrum by CMB is very important to identify the curvaton scenario through the consistency relation (21). If the curvaton once dominates the Universe, an entropy production process by its decay is imprinted in the gravitational wave background spectrum and can be confirmed by future space-based laser interferometer experiments. For the opposite case where the curvaton is a subdominant component before it decays, a large non-Gaussianity is predicted, which may be confirmed by Planck experiment. In this sense, the gravitational wave signal and non-Gaussian signal are complementary to each other. This allows us to probe the curvaton scenario for large parameter spaces, giving information on the properties of the curvaton such as its decay rate and amplitude, etc. It will in turn provide important information on high-energy physics beyond the reach of terrestrial experiments.

Acknowledgements

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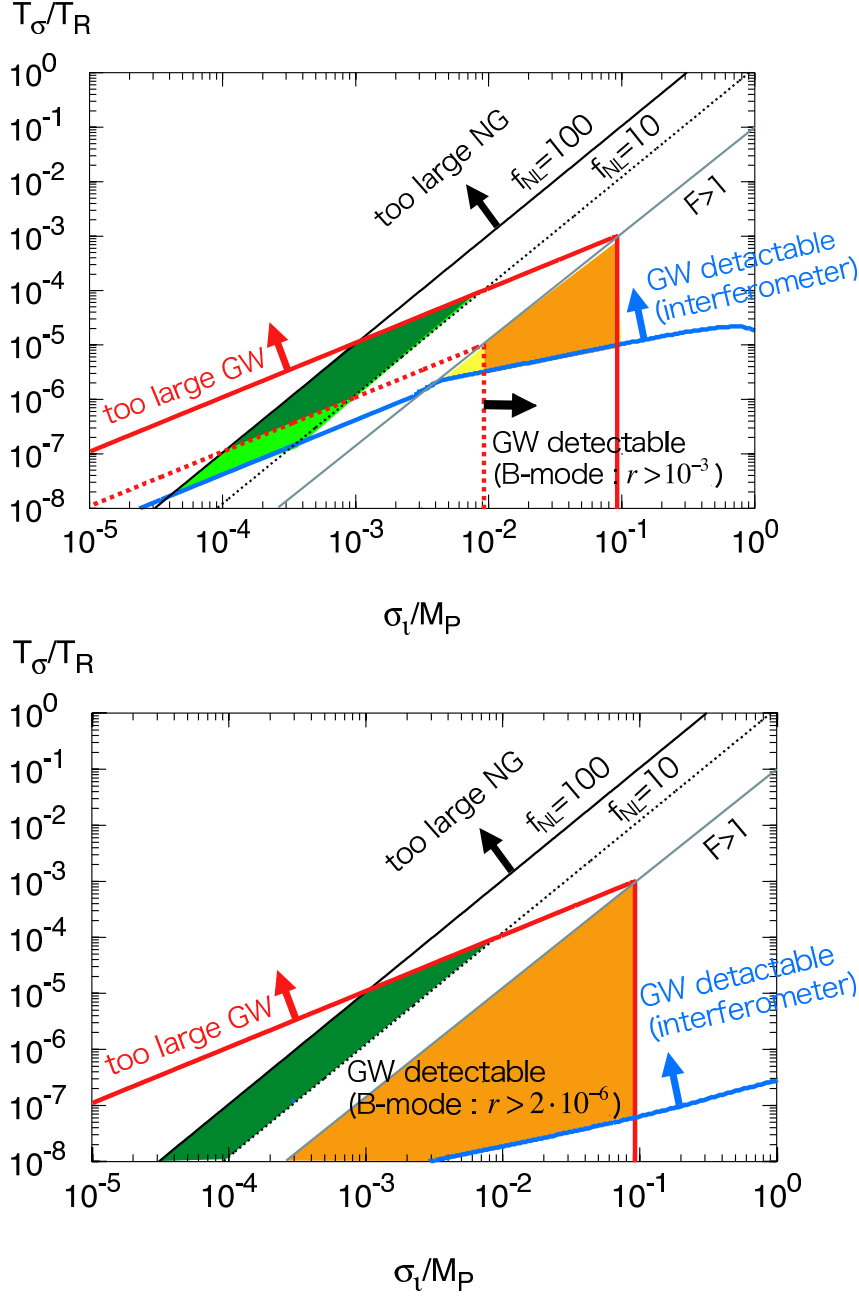[3] E. Komatsu *et al.* [WMAP Collaboration], arXiv:0803.0547 [astro-ph].

Figure 2: Range of the curvaton parameters σ_i/M_{Pl}-T_σ/T_R which can be probed by space-based laser interferometers. The upper panel represents the case with single ultimate-DECIGO and B-mode measurements down to $r = 10^{-3}$, while the lower panel shows an ideal case with correlation analysis of ultimate-DECIGO and B-mode measurements accesible to $r = 2 \times 10^{-6}$. Region above the red wedge is excluded since the tensor mode contribution to the CMB anisotropy becomes too large. Also shown there are contours of the non-linearity parameter f_{NL}. Upper left region above the solid line is disfavored by WMAP. In the green region all the curvaton parameters can be determined in terms of f_{NL} and r, while in the orange region they can be determined by F and r provided other sources of entropy production is absent. In the yellow region, F and r are not determined independently, and only the combination $rF^{-4/3}$ is determined.

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